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CLASSIFICATION OF LAKES ACCORDING TO TEMPERATURE.

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IN view of the increasing attention that is being given to the study of the temperature of the water in lakes and ponds it seems advisable to establish some system of classification by which we may group these bodies of water according to their temperature, thus giving additional value to the data accumulating on the subject. A suggestion for such a classification is here presented. It may add to a better understanding of the subject if we refer briefly to the temperature changes which take place in a body of water and the practical importance of the physical phenomena which they produce. We cannot do better, perhaps, than to take Lake Cochituate as an example and study it by the aid of the diagram in Fig. 1. The curves in this diagram are based on a seven years' series of weekly observations, but certain irregularities have been omitted for the sake of simplicity. If we trace the line of surface temperatures, we observe that during the winter the water immediately under the ice stands substantially at 32° F., though it may be added that the ice itself often becomes much colder than 32° at its upper surface. As soon as the ice breaks up in the spring the temperature of the water begins to rise. This increase continues, with some fluctuations, until about the first of August. Cooling then begins and continues regularly through the autumn until the lake freezes in December. If this curve of surface temperature were compared with the mean temperature of the atmosphere for the same period, a striking agreement would be noticed, and it would be seen that the water temperature is the higher of the two, — probably because of the direct heat received from the sun. In shallow ponds this effect is very marked, but in large, deep lakes, where the water circulates to considerable depths, the atmospheric temperature is usually higher than the water temperature.

The temperature at the bottom of Lake Cochituate during the winter, when the surface is frozen, is not far from that of maximum density (39.2° F.). The heaviest water, therefore, is at the bottom and the lightest at the top, the intermediate layers being arranged in the order of their density. Repeated observations have shown that the colder water occupies a comparatively thin stratum under the ice, and that the temperature at a depth of ten feet is not much lower than at the bottom. With these conditions the water is in comparatively stable equilibrium. There is no tendency for it to circulate vertically. It is in a condition of "inverse stratification," as Forel calls it, when the colder water is above the warmer. It is the "period of winter stagnation." In the spring when the ice breaks up the cold surface water becomes mixed to a certain extent with the warmer water below it, and the bottom temperature drops

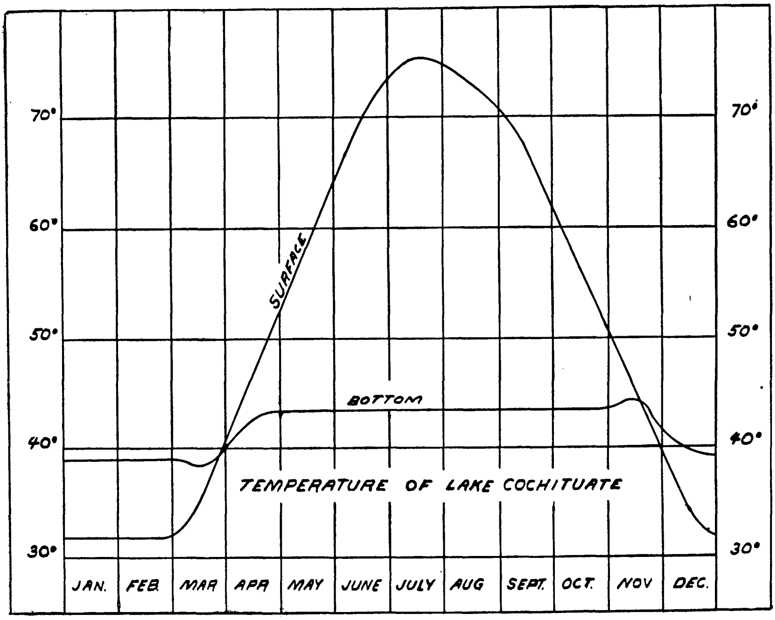

FIG. 1.

slightly. Soon the surface and bottom layers come to have substantially the same temperature, and vertical currents extend from top to bottom. This is the "period of spring circulation," or the "spring overturning." It lasts several weeks, but varies in duration in different years. As the season advances the surface water becomes warmer than that at the bottom, and finally the difference becomes so great that the wind is no longer able to keep up the circulation. Consequently, the bottom temperature ceases to rise, the water becomes "directly stratified," and the lake enters upon the period of "summer stagnation." During this period, which extends from April to November, the bottom temperature remains constant and the water below a depth of about twenty-five feet remains stagnant. This bottom temperature during the summer varies with different years, depending upon the meteorological conditions at the time when the period begins. In the autumn, as the surface cools, the water becomes stirred up to greater and greater depths, until finally the "great overturning" takes place, and all the water is in circulation. At this time there is a slight increase in the bottom temperature. Then follows the "period of autumnal circulation," during which the surface and bottom layers have substantially the same temperature. In December the lake freezes and "winter stagnation" begins.

Thus during the year there are two periods of circulation and two periods of stagnation. These physical changes have an important effect upon the quality of the water. During the stagnation periods much of the suspended matter in the water settles to the bottom, where there is already a large accumulation of organic matter. This decomposes, robbing the lower layers of water of all the oxygen present. Decomposition then goes on under the influence of the anærobic bacteria, and the water becomes charged with the products of decay. By the end of the stagnation period the lower layers have a very high color and a bad odor. At the overturning the foul water is carried into circulation, and its effect is noticed throughout the entire body of water. Nor is this all. The circulating water brings up from the bottom certain micro-organisms which have been lying dormant, and the products of decay alluded to become changed into food material suitable for them; consequently, the organisms develop and the quality of the water suffers.

This matter of stagnation with its unpleasant effects is an important one for water-works engineers to study. The growth of organisms is closely connected with the presence of organic matter at the bottom. Observations have shown that if the organic matter is absent the organisms do not grow to any great extent. The best modern practice in the construction of reservoirs for water supply, therefore, indorses the removal of the soil from all areas to be flooded. This, however, is usually a matter of great expense, and, for that reason, some engineers do not consider it advisable to remove the soil from very deep reservoirs. In the opinion of the writer this position is well taken only in the case of reservoirs so situated and so deep that there is practically no circulation of the water at the bottom, and, therefore, no opportunity for any foul matter to be carried upwards.

The requisite depth for the attainment of such a condition is at present unknown. We know that in some very deep lakes the water at the bottom remains constantly at the temperature of maximum density, but we do not know how much this depth must be diminished in order to have circulation take place. Moreover, the depth is not the only factor concerned. The size and shape of the lake, its geographical location, and the nature of the surrounding country all have their effect upon the circulation of the water. As the vertical circulation of water can be studied best by means of its temperature, we see how valuable it would be to have regular and continued temperature observations made at various depths in our deep lakes and ponds. The observations thus far made are far too few to enable us to establish the point desired.

According to the classification here suggested, lakes and ponds are divided into three types, according to their surface temperatures, and into three orders, according to their bottom temperatures. The resulting nine classes are shown in Fig. 2. On these diagrams the boundaries of the shaded areas represent the limits of the temperature fluctuations at different depths.

The horizontal divisions represent temperatures in Fahrenheit degrees increasing towards the right, and the vertical divisions represent depth. The three types of lakes are designated as *polar*, *temperate*, and *tropical*. In lakes of the polar type the surface temperature is never above that of maximum density; in lakes of the tropical type it is never below that point; in lakes of the temperate type it is sometimes below and sometimes above it. This division into types corresponds somewhat closely with geographical location.

The three orders of lakes may be defined as follows: lakes of the first order have bottom temperatures which are practically constant at or very near the point of maximum density; lakes of the second order have bottom temperatures which undergo annual fluctuations, but which are never very far from the point of maximum density; lakes of the third order have bottom temperatures which are seldom very far from the surface temperatures. The division into orders corresponds in a general way to the characters of lakes; *i.e.*, size, contour, depth, surrounding topography, etc.

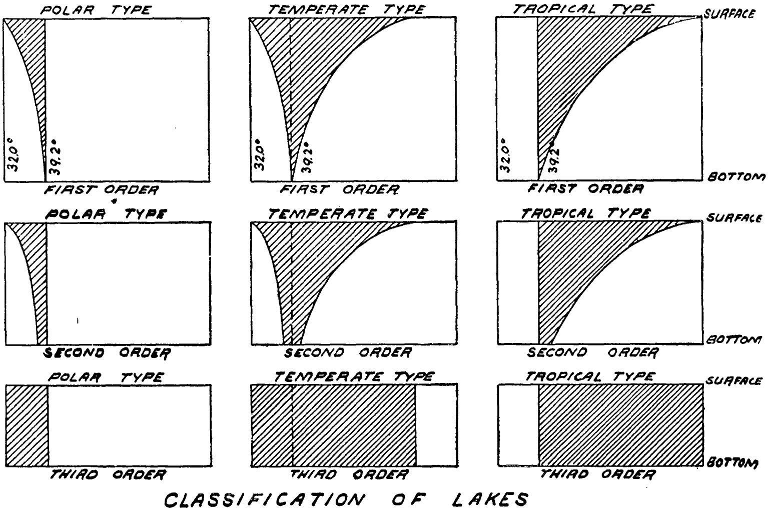

FIG. 2.

This classification is essentially the same as that recently proposed by Forel. He divides lakes into three types, polar, temperate, and tropical, but bases the distinction upon bottom temperatures instead of surface temperatures, as follows:

1. *Tropical Type:* Temperature of deep layers varies from and above maximum density.

2. *Temperate Type:* Temperature of deep layers varies above and below maximum density.

3. *Polar Type:* Temperature of deep layers varies from and below maximum density.

He subdivides each type into two classes, deep and shallow, defining deep lakes as those which have a constant bottom temperature, and shallow lakes as those which have a variable bottom temperature. This subdivision is not a happy one, as observation shows that there are many lakes which would unquestionably be called "deep" which have a variable bottom temperature.

The temperature changes which take place in the nine classes of lakes according to our system of classification are exhibited in another manner in Fig. 3. These diagrams show by curves the surface and bottom temperatures for each season of the year, the times being plotted as abscissæ and the temperatures as ordinates. The shaded areas show the difference between the surface and bottom temperatures, the wider the shaded area, the greater being the difference.

A study of these diagrams brings out some interesting facts concerning the phenomena of circulation and stagnation. In Fig. 2 it will be seen that the circulation periods occur when the curve showing the temperatures at various depths becomes a vertical line; that is, when the water all has the same temperature. The stagnation periods are shown by the line being curved, the top to the right when the warmer layers are above the colder, and to the left when the colder layers are above the warmer. In Fig. 3 the circulation periods are indicated by the surface and bottom temperature curves coinciding, and the stagnation periods by these lines being apart. The distance between the lines indicates, to a certain extent, the difference in density between the top and bottom layers, and we see that the farther apart the lines become the less likelihood there is that the water will be stirred up by the wind.

In lakes of the polar type there is but one opportunity for vertical circulation (except in the third order), namely, in the summer season, when the water approaches the temperature of maximum density. In a lake of the first order, that is, in one where the bottom temperature remains constantly at 39.2°, the circulation period would be very short indeed, if not lacking altogether. In a lake of the second order circulation might and probably would continue for a longer period. In a lake of the third order the water would be in circulation nearly all the time except when frozen. The minimum temperature limit indicated for this order, *i.e.*, 32° at all depths, would be possible only in very shallow bodies of water, and would simply indicate that all the water was frozen; the temperature of the ice would probably be below 32° at the surface. It is probable that very few polar lakes exist.

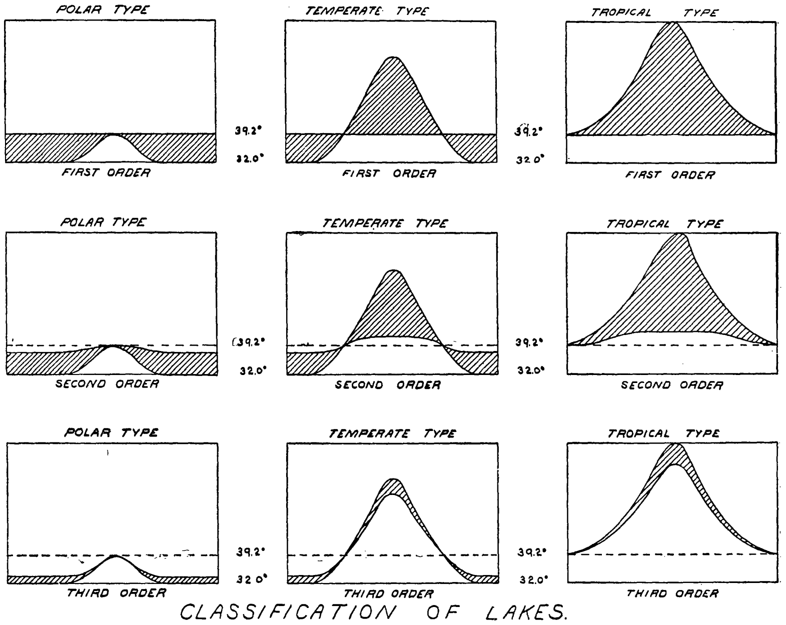

FIG. 3.

In lakes of the tropical type there is likewise but one period of circulation each year (except in the third order). This would occur not in summer, but in winter. In the first order this circulation period would be brief or entirely wanting; in the second it would be of longer duration; in the third order the water would be liable to be in circulation the greater part of the year. Tropical lakes are quite numerous, but observations are lacking to place them in their proper order.

Most of the lakes of the United States belong to the temperate type. In this type there are two periods of circulation and two periods of stagnation (except in the third order), as we have seen illustrated in the case of Lake Cochituate. In lakes of the first order the circulation periods would be very short or entirely wanting; in the second order the circulation periods would be of longer duration; in the third order the water would be in circulation throughout the year when the surface was not frozen.

If we recapitulate in tabular form, we have the following:

CIRCULATION PERIODS.

	Polar Type.	Temperate Type.	Tropical Type.
1st Order.	One circulation period possible, in summer, but generally none.	Two circulation periods possible, in spring and fall, but generally none.	One circulation period possible, in winter, but generally none.
2d Order.	One circulation period, in summer.	Two circulation periods, in spring and autumn.	One circulation period, in winter.
3d Order.	Circulation at all seasons, except when surface is frozen.	Circulation at all seasons, except when surface is frozen.	Circulation at all seasons.

Speaking in very general terms, we may say that lakes of the first order have no circulation; lakes of the third order have no stagnation (except in winter); and lakes of the second order have both circulation and stagnation.

In view of the comparatively few series of observations of the temperature of our lakes, the writer refrains from making any classification of the lakes of the United States, but the results thus far obtained seem to indicate that the first order will include only those lakes more than about two hundred feet in depth, such, for instance, as the Great Lakes, Lake Champlain, etc.; the second order will include those whose depth is less than about two hundred feet, but greater than about thirty feet; and the third order will include those whose depth is less than twenty-five feet. These boundaries are only approximate, and it should be remembered that depth is not the only factor which influences the bottom temperature.

Instead of citing long tables of figures giving the results thus far obtained, which would materially lengthen this paper, the writer prefers to cite a list of references which the reader may consult.

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